NIST Research on Color Quality of SSL Sources

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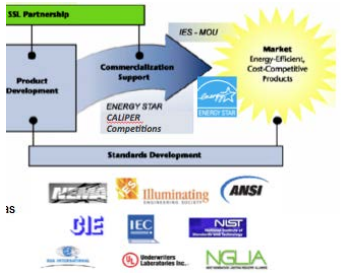
OUTLINE

1. Overview of NIST work on SSL standardization supported by DOE
2. NIST research and standards work on chromaticity and color rendering
3. Vision experiment on white light chromaticity
   – Preferred ranges of Duv

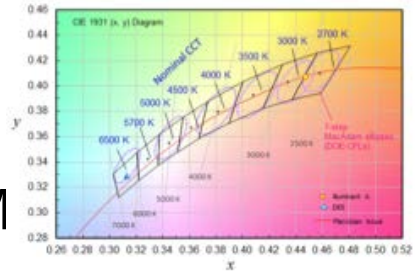
Overview of NIST work on SSL standardization

DOE initiated SSL standards work from the meeting in Washington DC on March 1, 2006.



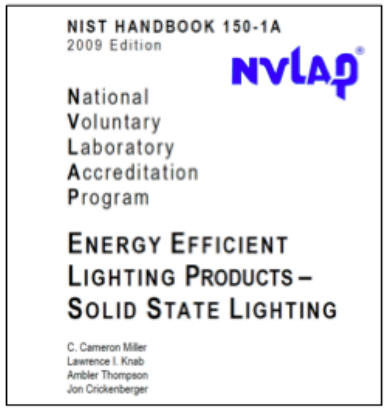
- NIST has funding support from DOE since 2006 for SSL standards development.

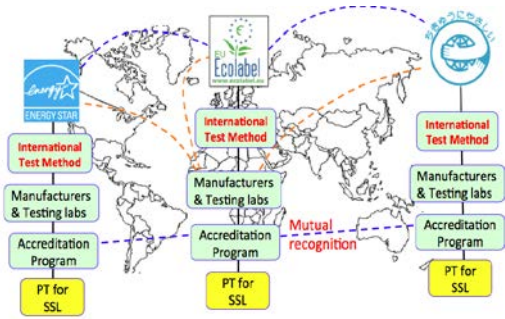
- NIST led development of LM-79.
- NIST led development of ANSI C78.377.
- NIST led development of LM-85 (to be published).



- NIST contributed to developments of LM-80, TM 21 (2011), RP-16, LM-82 (2012), …..

- NIST worked with NVLAP to develop the NVLAP SSL testing accreditation program (needed for Energy Star).
- NIST continues providing SSL Proficiency Testing, serving over 100 labs in US and overseas since 2009.
- IEA 4E Solid State Lighting Annex started from 2010. DOE represents USA. NIST participates as US expert member and leads Task 2 SSL Testing. NIST led IC2013 comparing over 50 labs worldwide on SSL measurement.
- NIST is leading development of the international SSL test method standard (CIE TC2-71)





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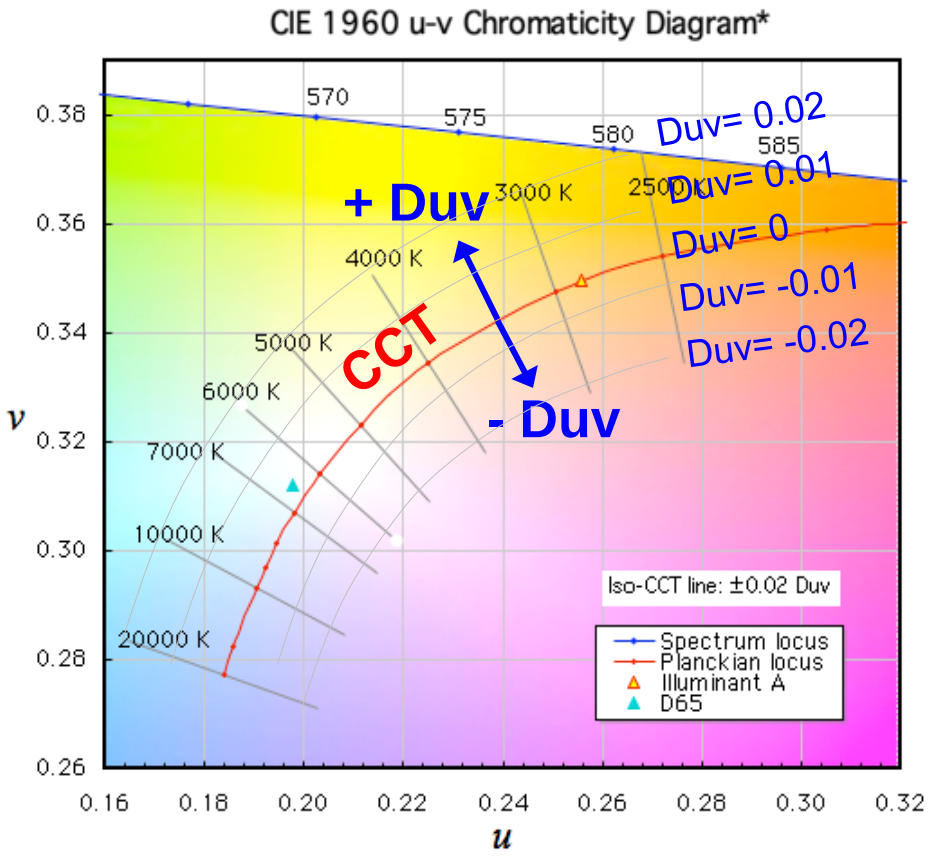
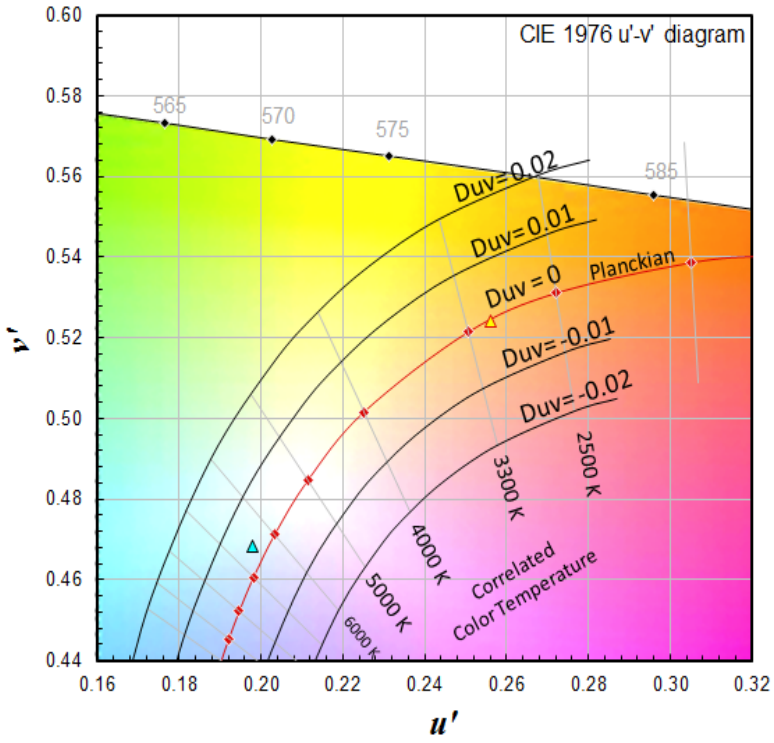
Duv defined in ANSI C78.377

Closest distance from the Planckian locus on the (*u'*, 2/3 *v'*) diagram, with + sign for above and - sign for below the Planckian locus.

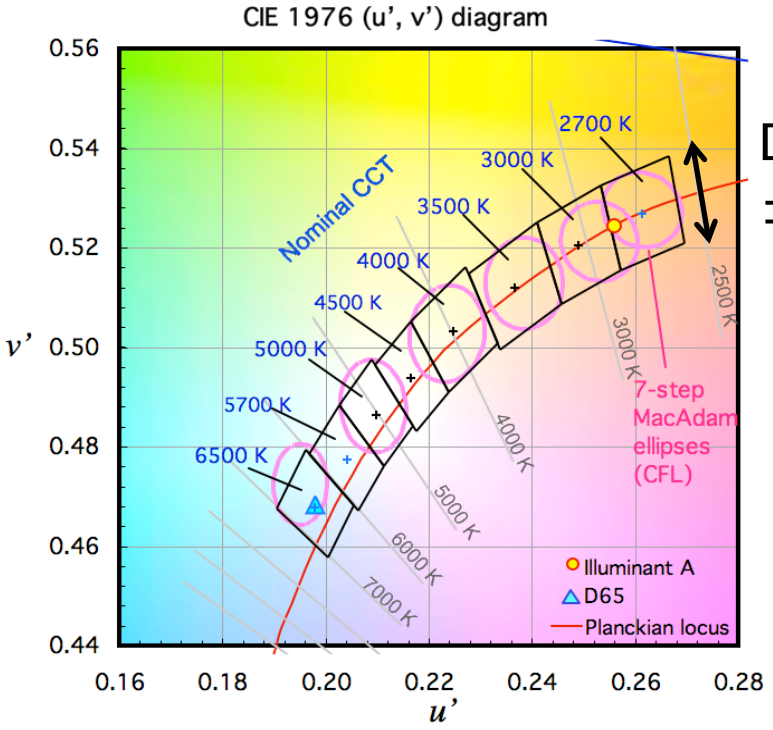


Duv scale on (*u'*, *v'*) diagram



ANSI C78.377-2008

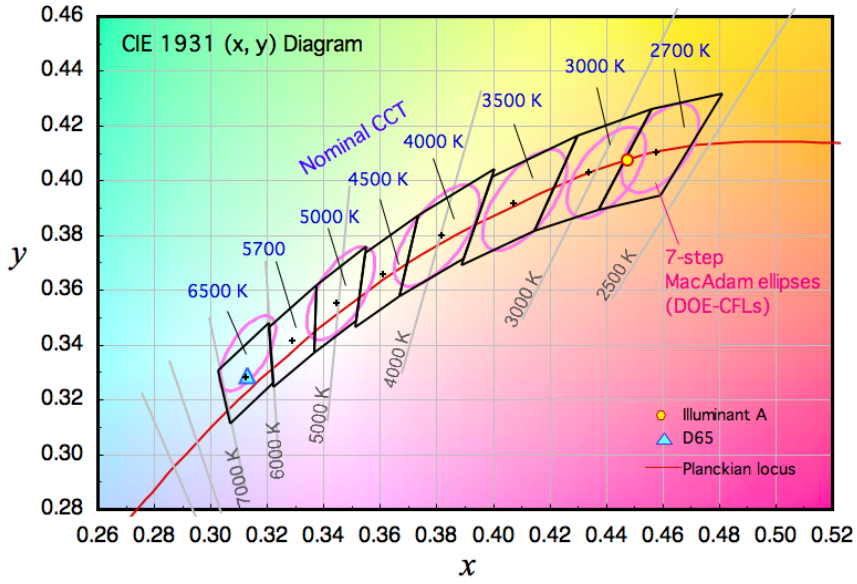
Specifications for the Chromaticity of SSL products



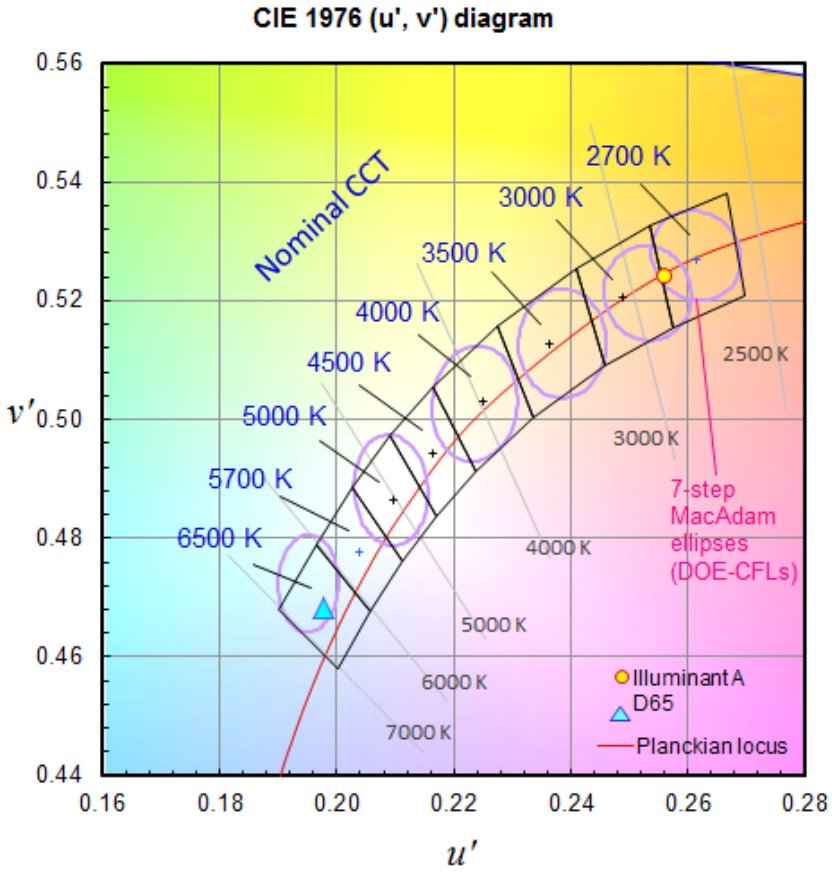
Duv
±0.006

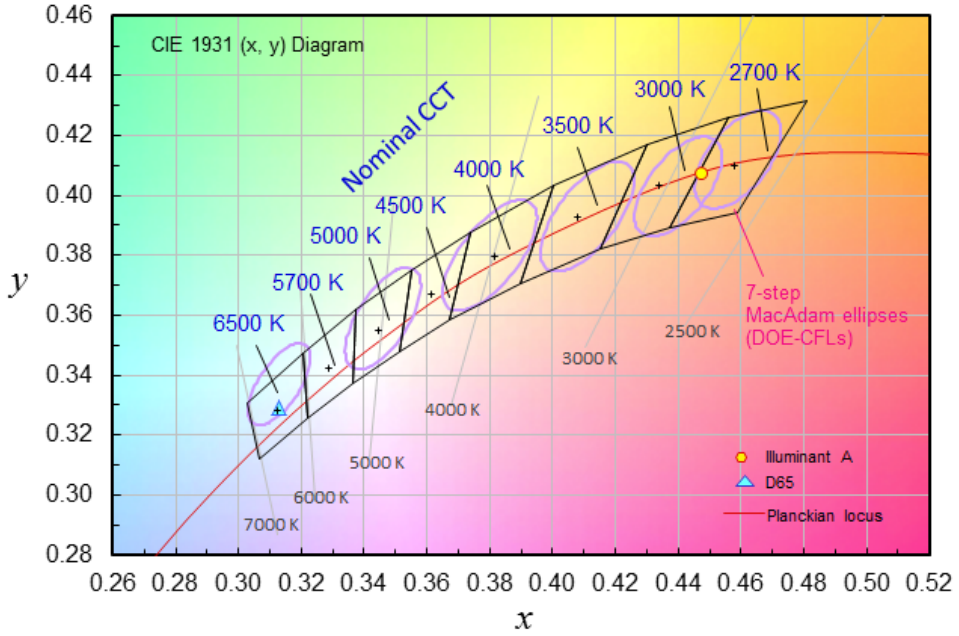
- Major contribution by NIST
- Used by ENERGY STAR and DOE programs for SSL and internationally.
- Basis for color binning of white LED products.

CIE 1931 (*x*, *y*) Diagram



ANSI C78.377-2011 Revision





Smooth boundary lines.

Further proposals

- Move all center points onto Planckian locus
- Add 2500 K and 2200 K bins

Practical Use and Calculation of CCT and Duv

Yoshi Ohno
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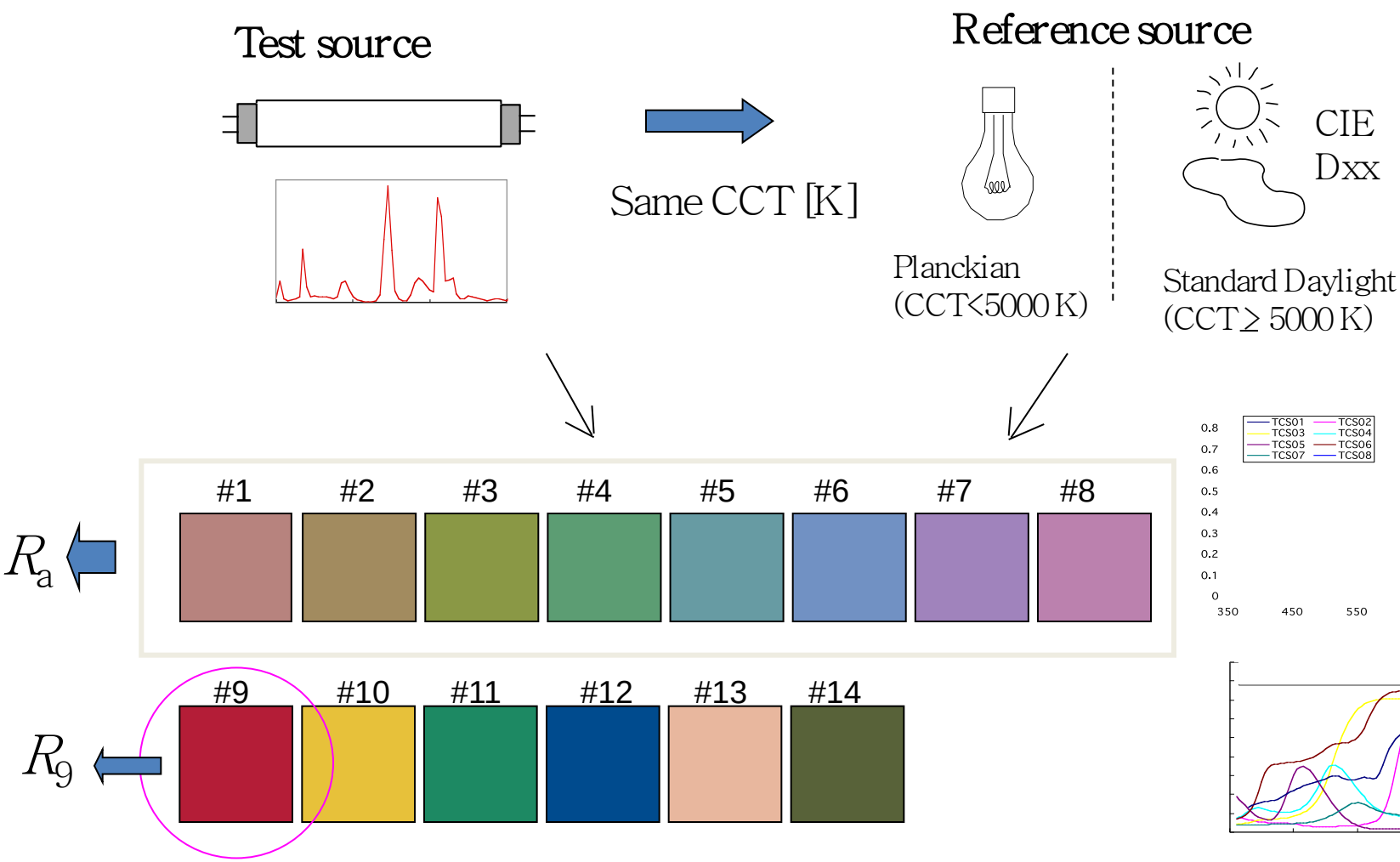
ABSTRACT Correlated color temperature (CCT) is often used to represent chromaticity of white light sources, but chromaticity is two-dimensional, and another dimension, the distance from the Planckian locus, is often missing. Duv is defined in ANSI C78.377 for this purpose but is not yet widely used. In this article, the use of a combination of CCT and Duv is proposed as an intuitive expression of chromaticity of white light sources for general lighting. In addition, this article presents practical calculation methods to calculate CCT and Duv, having sufficient accuracy, within an error of 1 K, in a wide range of chromaticity, from 1000 to 20,000 K in CCT and −0.03 to 0.03 in Duv.

KEYWORDS chromaticity, correlated color temperature, Duv, light source, Planckian locus

LEUKOS 10:1, 47-55, 2014 (DOI: 10.1080/15502724.2014.839020)

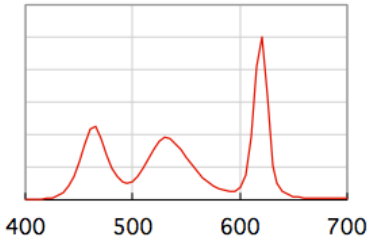
Investigating problems of the CRI

Color Rendering Index (CRI) CIE 13.3



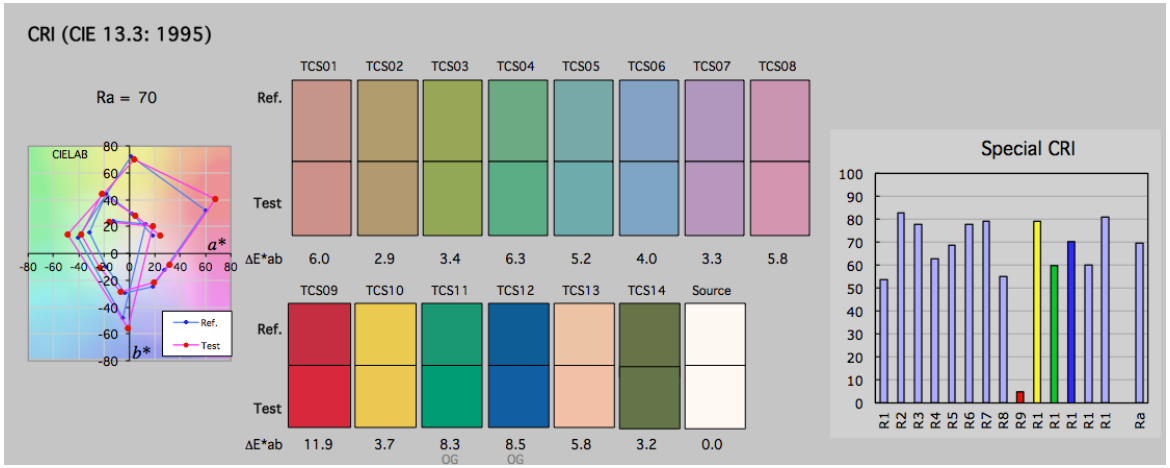
Problems of CRI

1. CRI (Ra) badly penalizes visually preferred lights

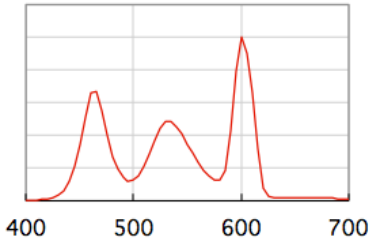


CCT 4929 K, Duv-0.001

CRI Ra = 70

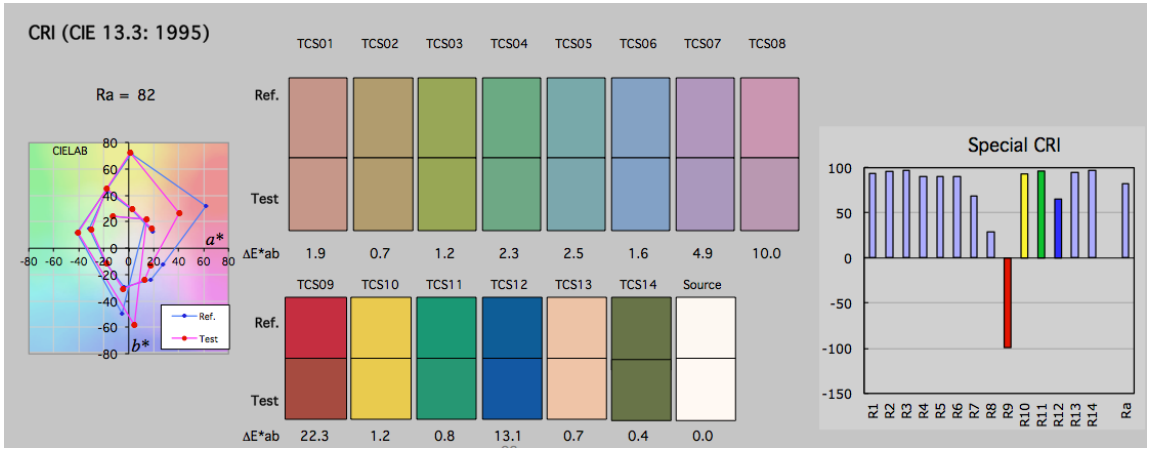


2. Good CRI (Ra) score does not guarantee good color rendering



CCT 5020 K, Duv 0.000

CRI Ra = 82, R9 = -99

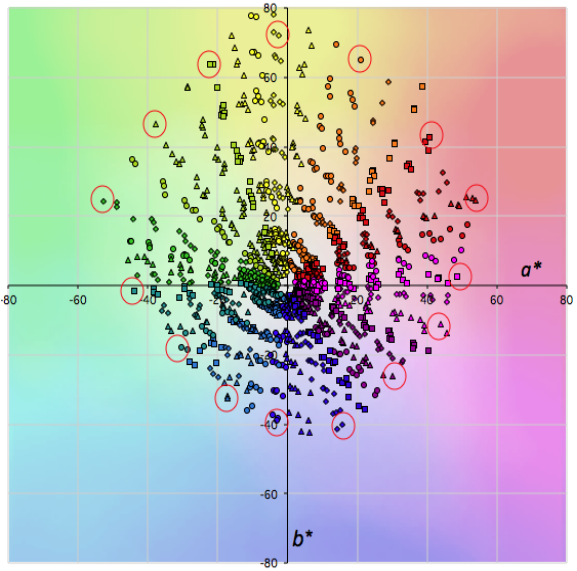


Color Quality Scale (CQS)

developed to improve CRI on these problems

- Improvement of CRI, produces one number score that correlates well with perceived naturalness for real objects.
  - 15 saturated test color samples

  - Update the old formulae in CRI
    - CIELAB color space
    - CMCCAT2000 chromatic adaptation
    - 0 to 100 scale
    - RMS averaging of color differences
  - Saturation factor (address the Hunt effect)

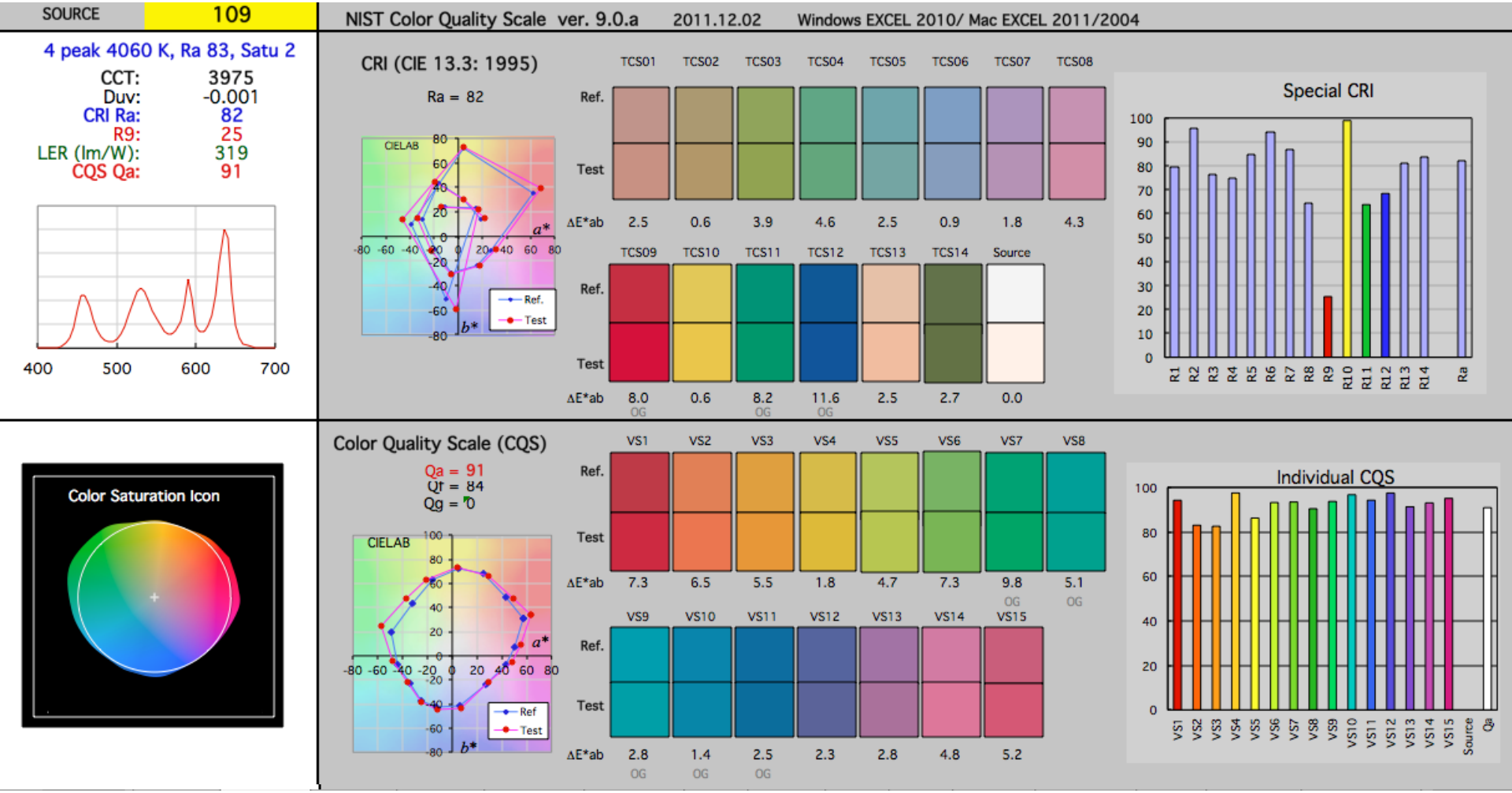


Standards work for new metric is still on-going (in CIE, IES)

CQS is used as a tool for color quality design.

W. Davis and Y. Ohno, Color Quality Scale, Optical Engineering **49** (3), 033602 March 2010

CQS 9.0 EXCEL sheet (Color Rendering Simulation)



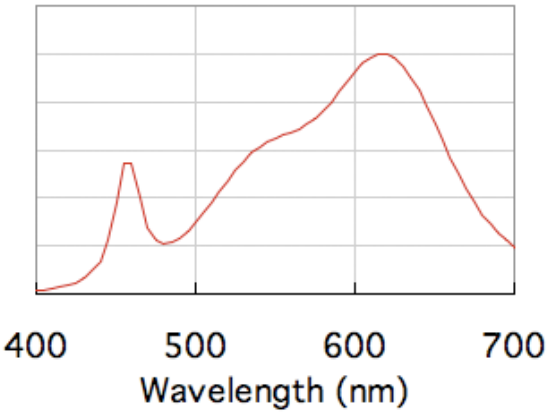
Used by many companies as a design tool for color quality

Looking at “Luminous Efficacy of Radiation”

B-Y + broad Red

CCT: 3000
Duv: 0.000
CRI Ra: 90
R9: 45

LER (lm/W): 310
CQS 89

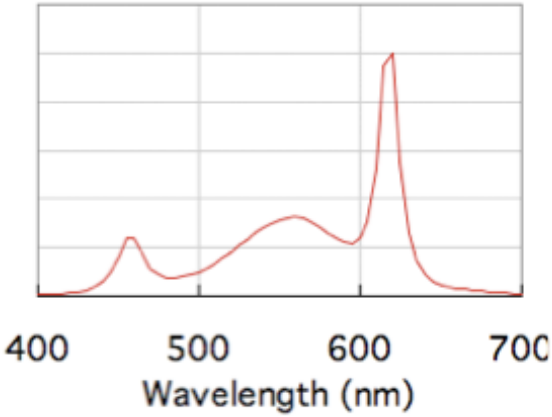


LER= 310 lm/W

B-Y + narrow Red

CCT: 3000
Duv: 0.000
CRI Ra: 90
R9: 30

LER (lm/W): 375
CQS 88

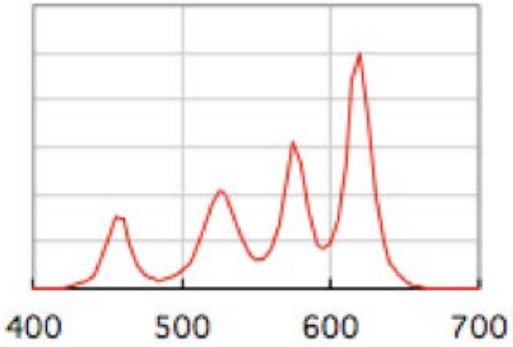


LER= 375 lm/W

RGBA (simulation)

(457/526/576/619)

CCT: 3000
Duv: 0.000
CRI Ra: 91
R9: 32
LER (lm/W): 382
CQS Qa: 90



LER= 382 lm/W

~20 to 25 % increase

Narrowband theoretically more efficient

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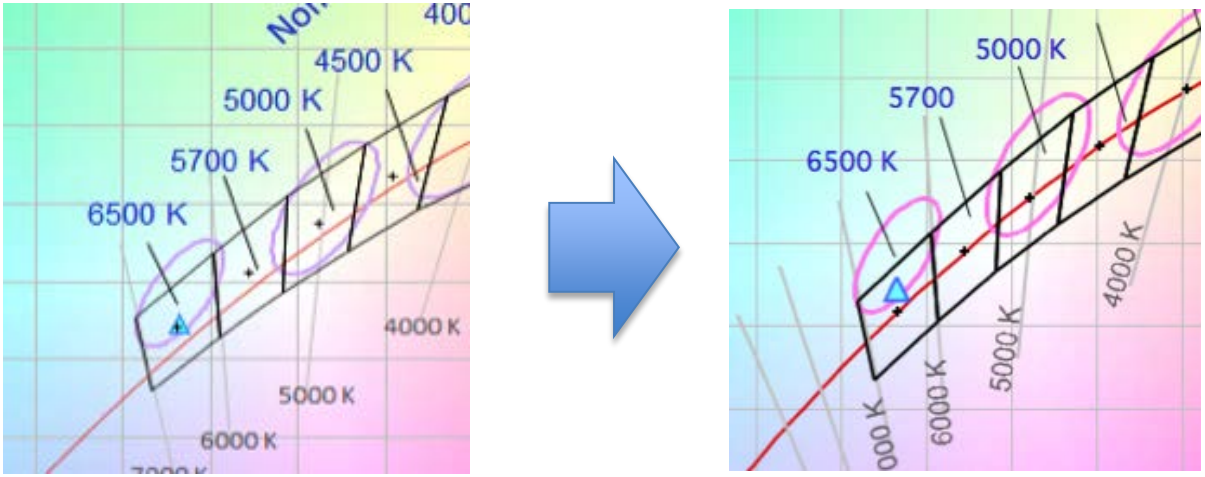
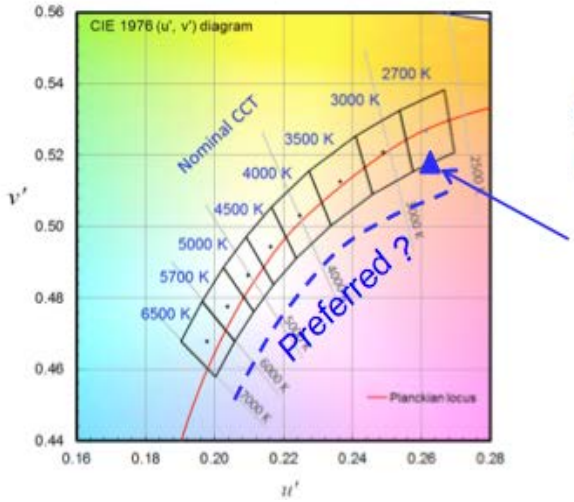
Collaboration with Mira Fein, Psychology Department, Oberlin College, Oberlin, Ohio (NIST Guest Researcher under NIST Summer Undergraduate Research Fellowship Program)

Background

Proposal in ANSI C78.377 WG

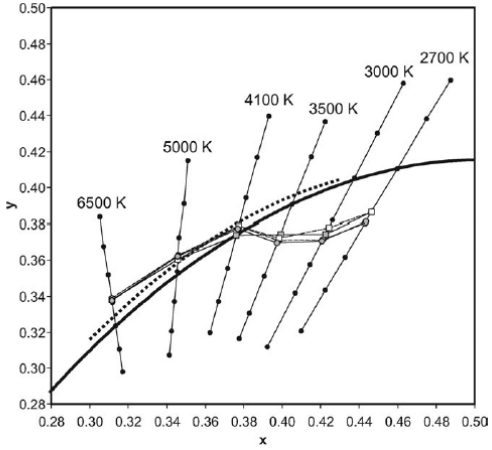


Anecdotes say …



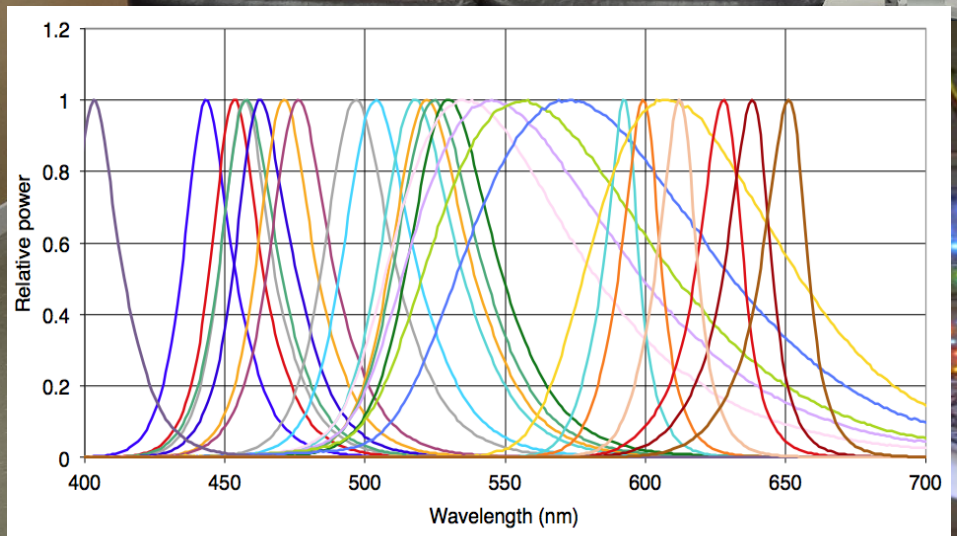
An example in neodymium lamp

Study by LRC

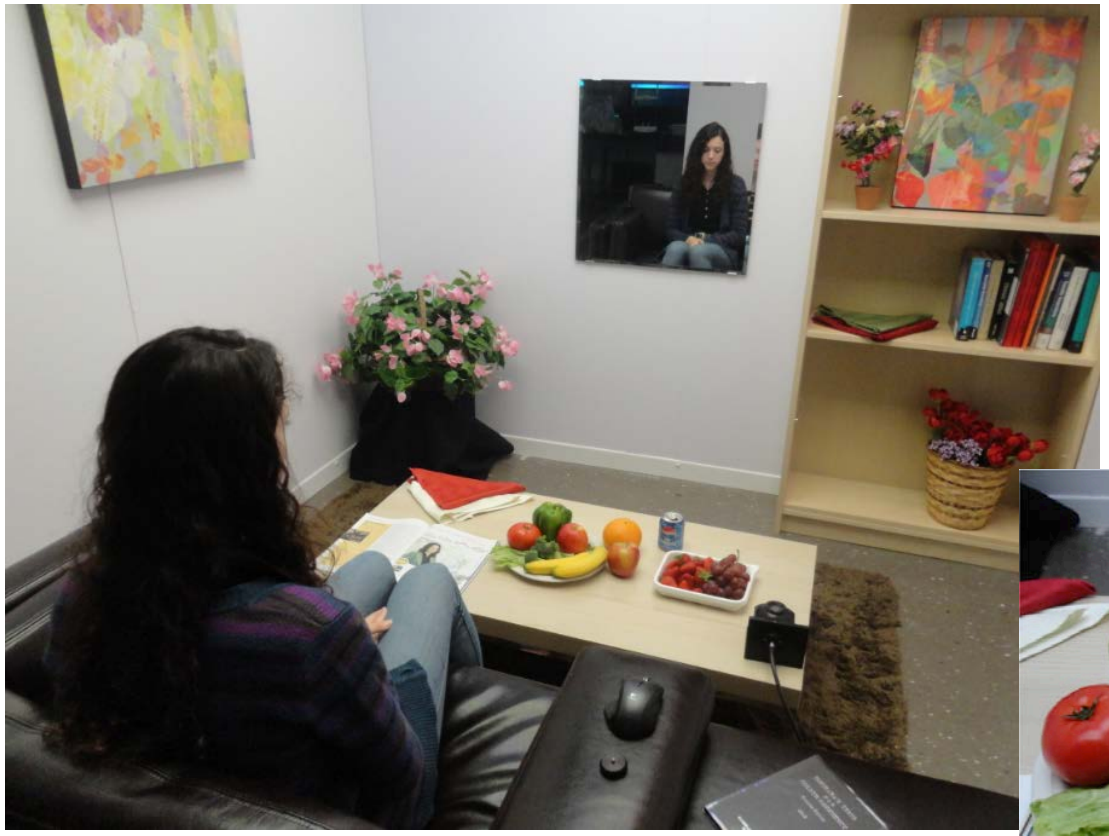


NIST Spectrally Tunable Lighting Facility

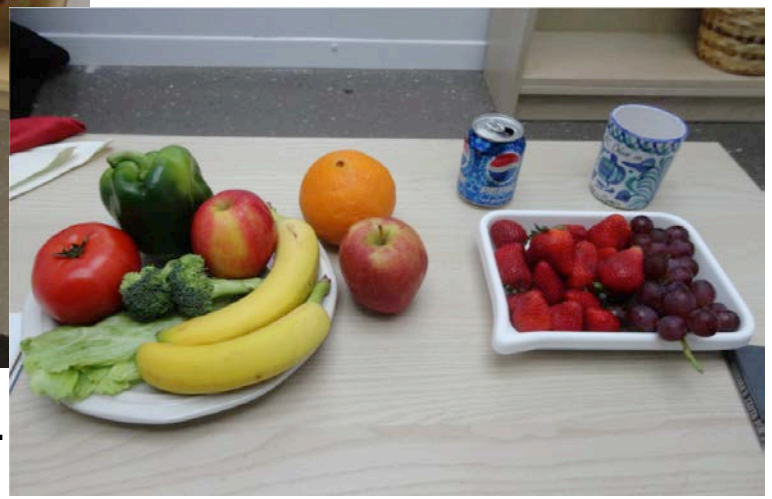
NIST Spectrally Tunable Lighting Facility



Experimental Setting

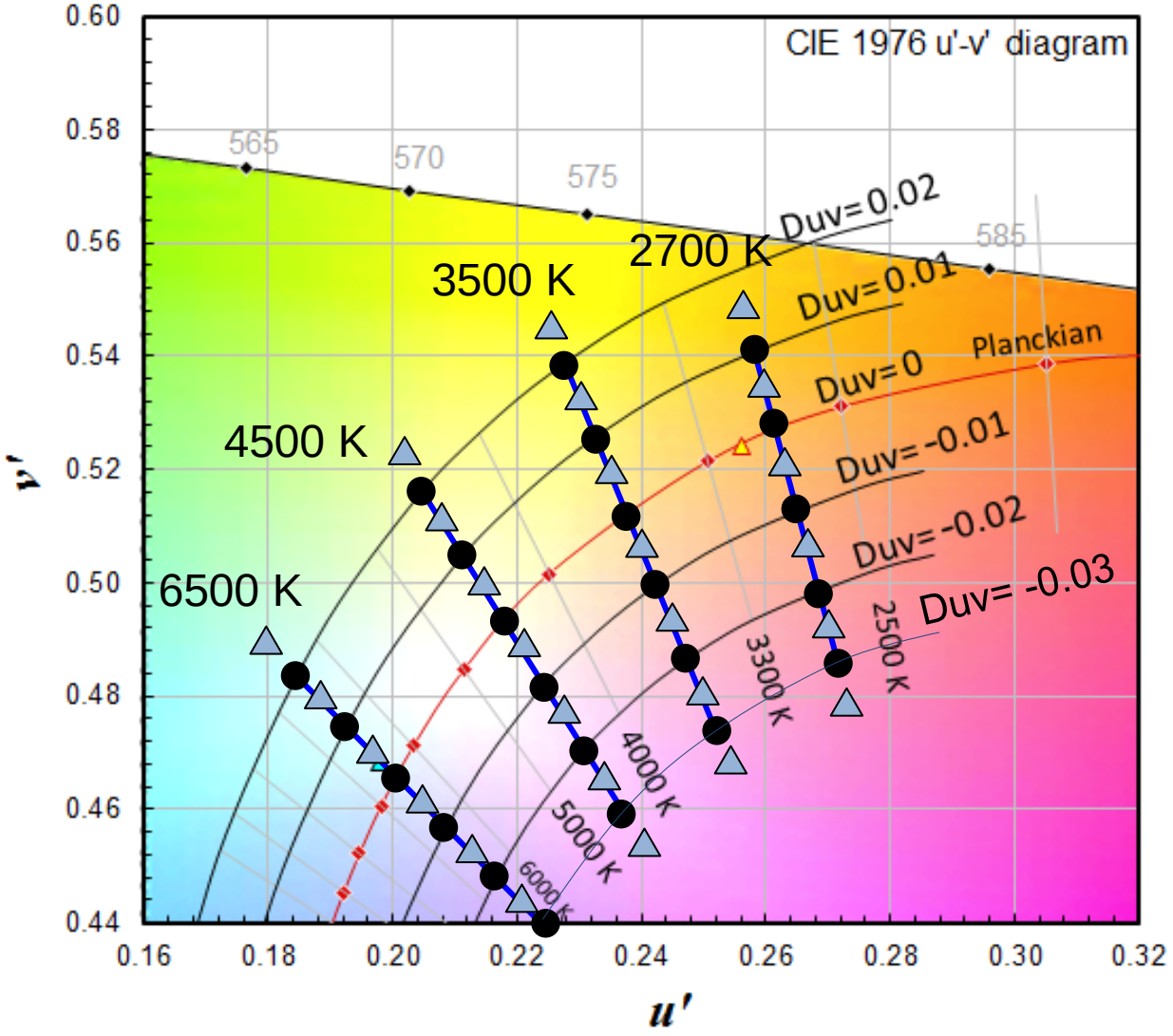


Real fruits on the table
(refreshed every few days)



- ~300 lx on the table (variations within ±1 %).
- Subjects viewed fruits on the table, face/hand skin tone in mirror and the entire room.
- 18 subjects, 19 to 70 years old. 11 males, 7 females.
- Neutral light grey walls / brownish walls

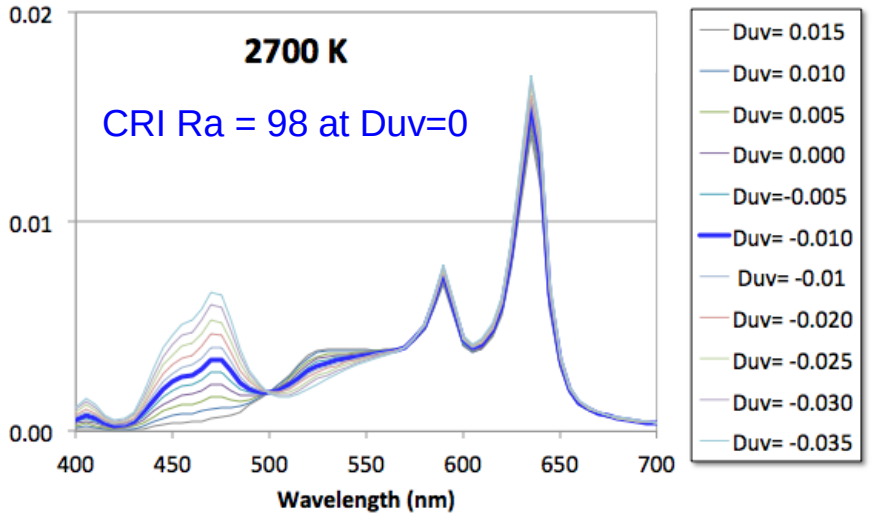
Experimental Design

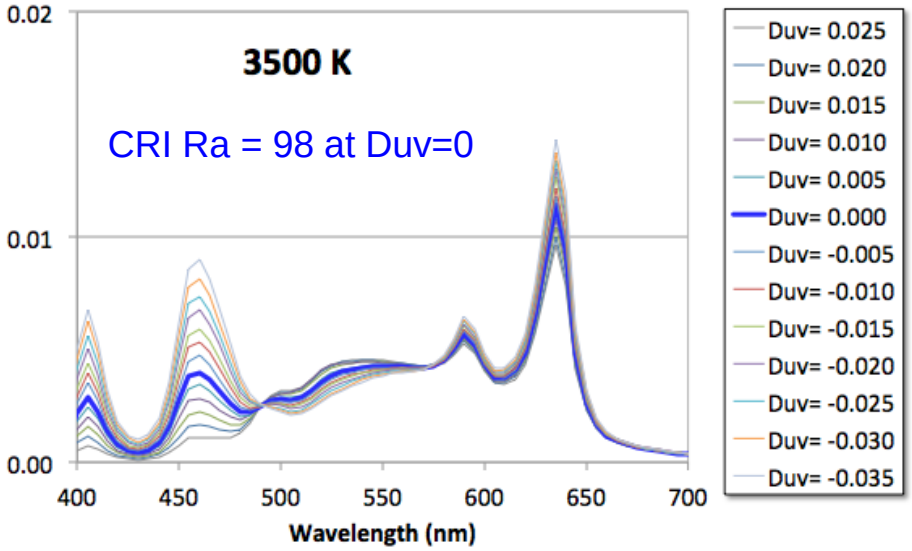


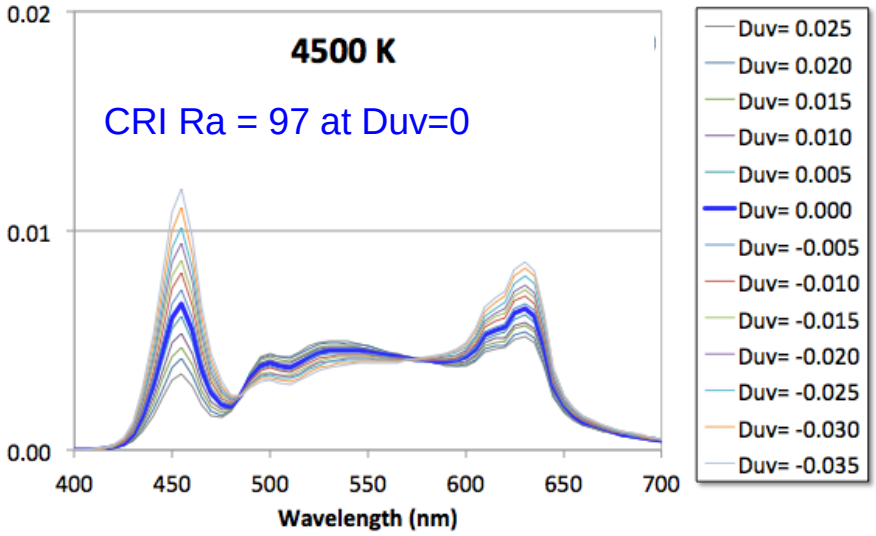
4 CCTs,
6 Duv points at each CCT,
23 points total for experiment.

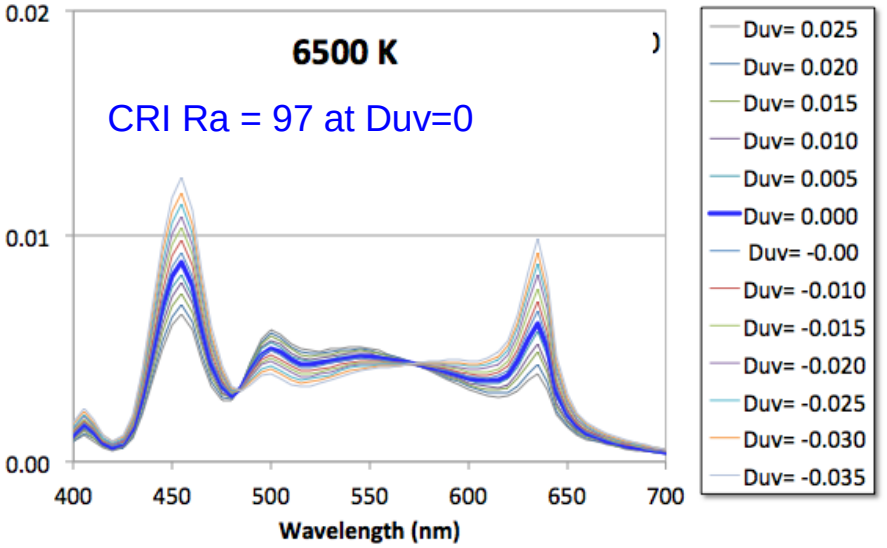
Plus, points in between and outside, total **50** points were set.

Light spectra used

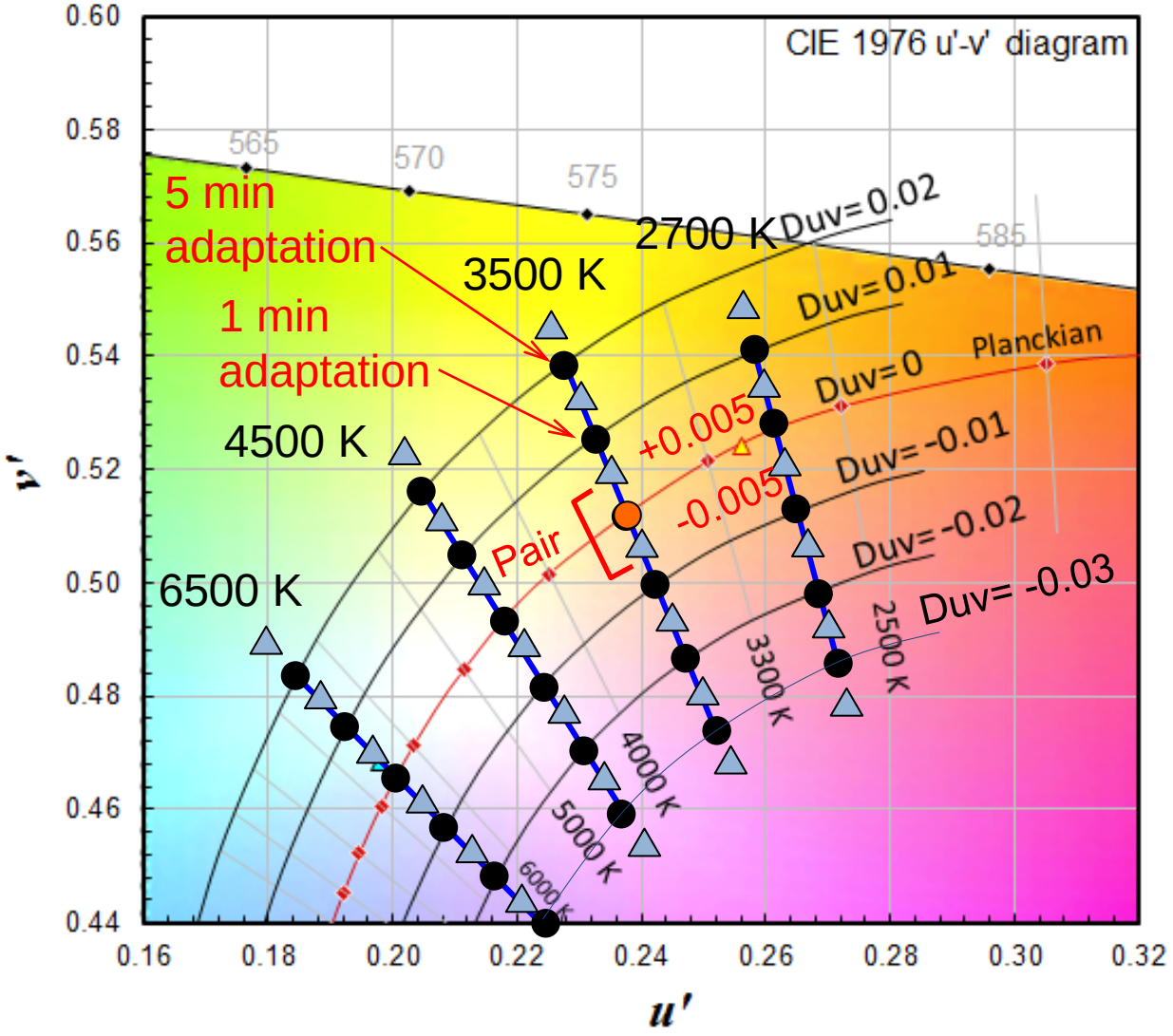








Experimental Procedures

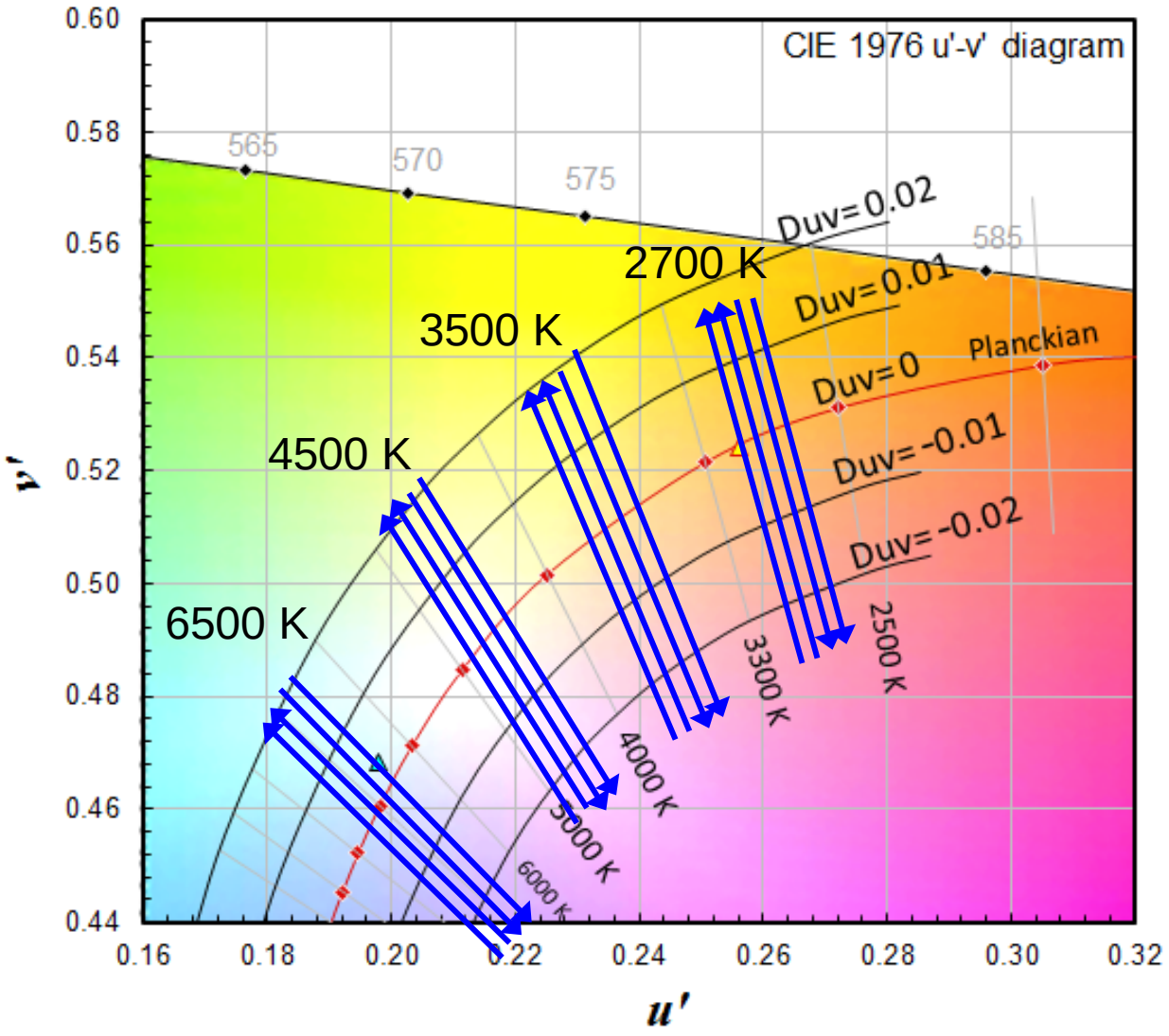


1) Adaptation

2) "Is this light acceptable?"

3) "Which light looks more natural?"

Experimental Procedures



- **6 Duv points at each CCT**
- **2 directions for each CCT**
- **4 CCTs**
- **2 repeated runs for each condition**

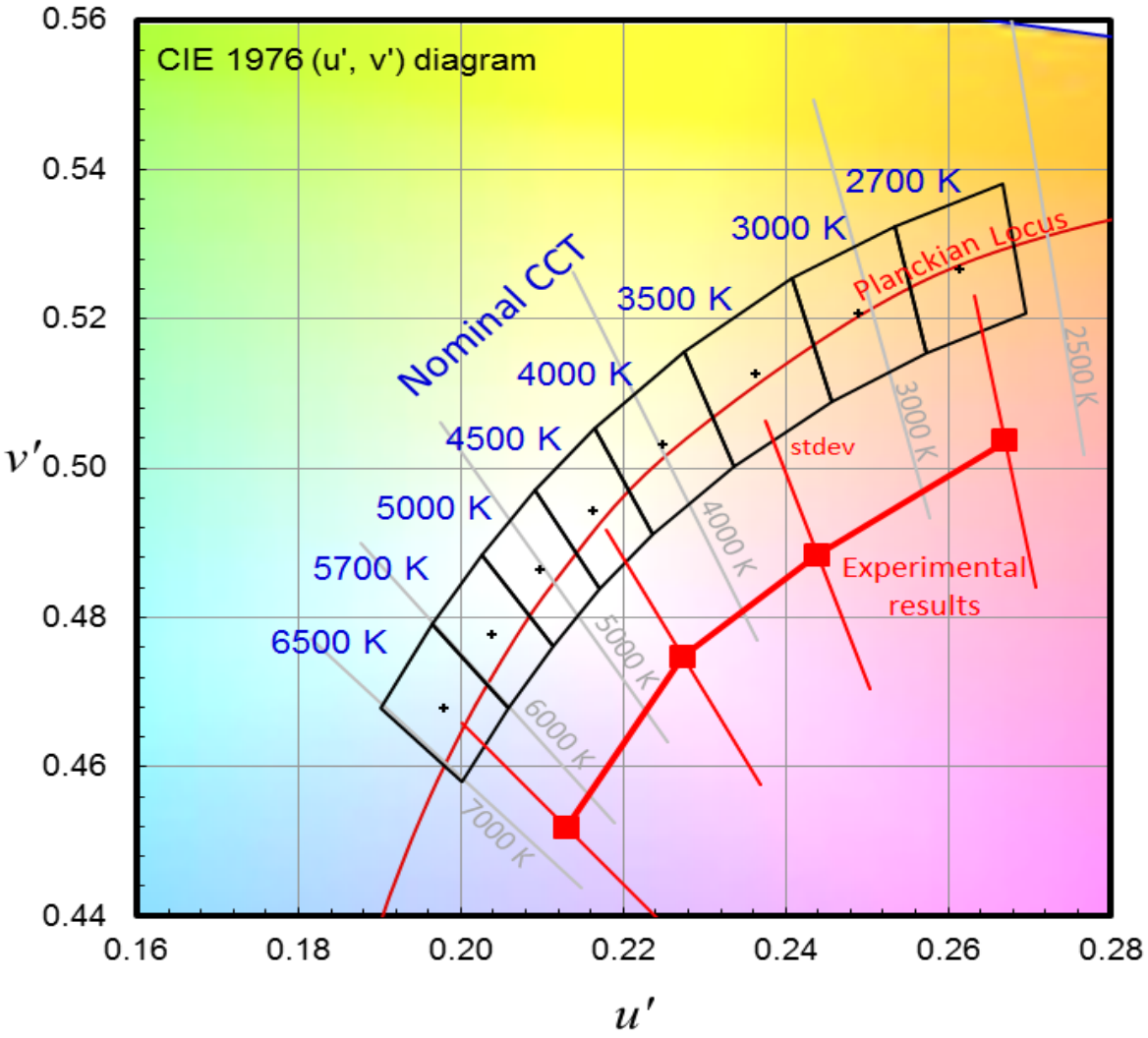
Total 16 runs,
96 comparisons of pairs of lights per subject.

Took ~ 4 h per subject.

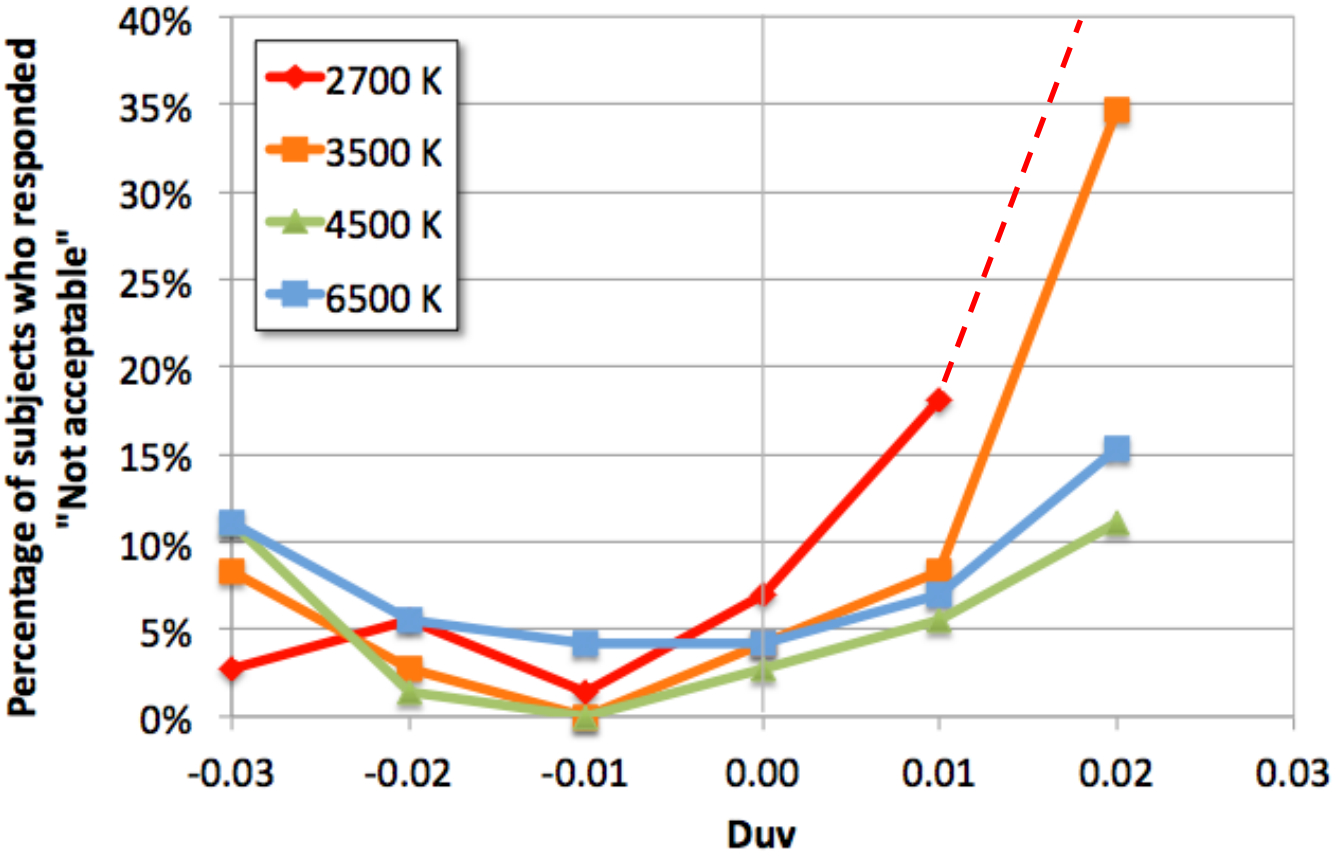
Brownish wall experiments with six subjects.

Whole experiment took one month.

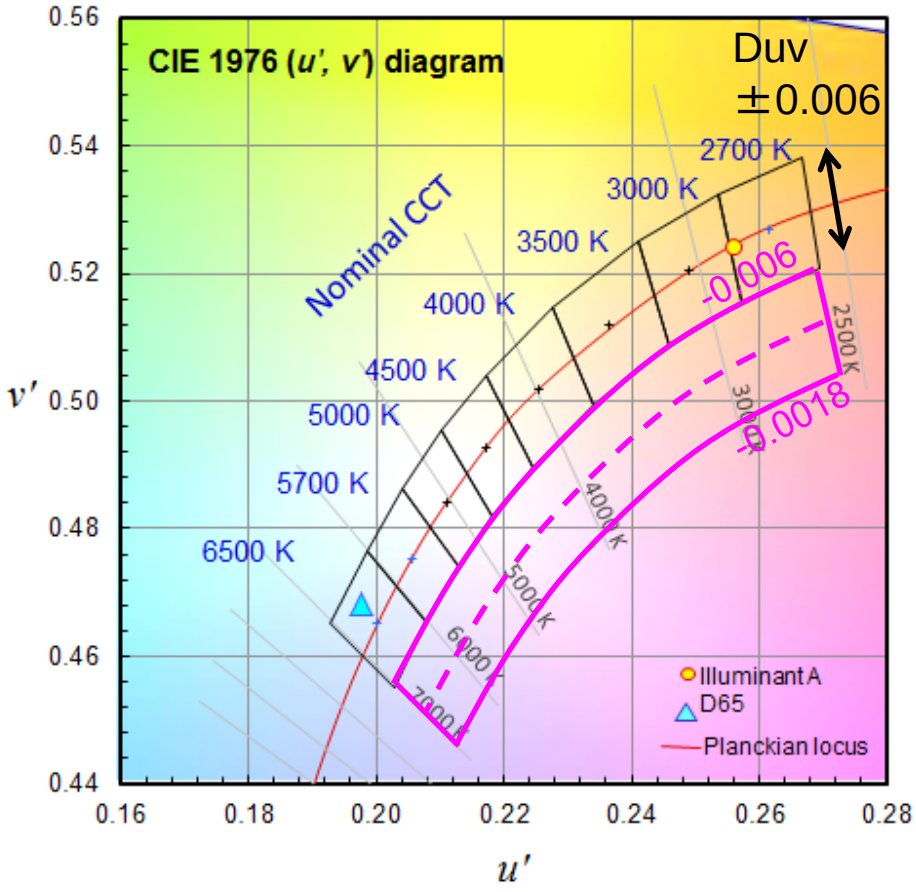
Results


CIE 1976 (u', v') diagram
0.56
0.54
0.52
0.50
0.48
0.46
0.44
v′
0.16
0.18
0.20
0.22
0.24
0.26
0.28
u′
Nominal CCT
2700 K
3000 K
3500 K
4000 K
4500 K
5000 K
5700 K
6500 K
Planckian Locus
stdev
Experimental results
2500 K
3000 K
4000 K
5000 K
6000 K
7000 K

Results of “Is this light acceptable?”

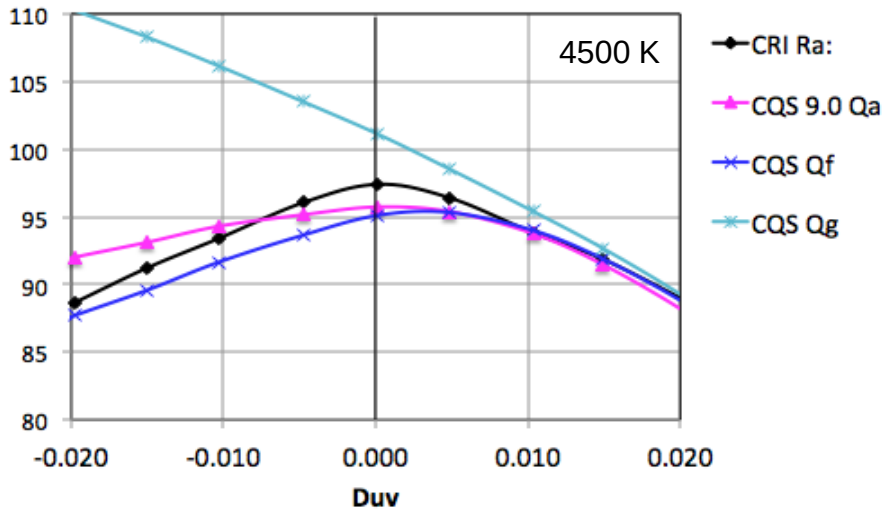


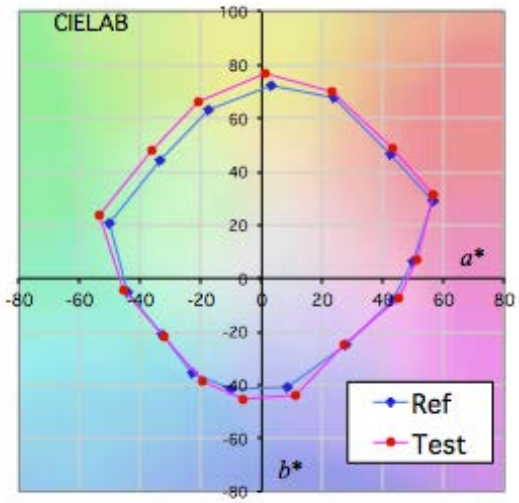
Discussions



- It would be okay to shift all center points onto Planckian locus
  → makes LED binning simpler
- Another region can be specified
  → possibly provides new category of "preference" products
  → utilize out-of-spec LEDs
- Bad news: Luminous efficacy drops slightly at lower Duv points
  → ~ 7 % at Duv= - 0.0012
- Good news: negative Duv carries benefits of increased color gamut (incl. perceived brightness)

Discussions





4500 K
Duv=-0.015

- It would be okay to shift all center points onto Planckian locus
  → makes LED binning simpler
- Another region can be specified
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  → utilize out-of-spec LEDs
- Bad news: Luminous efficacy drops slightly at lower Duv points
  → ~ 7 % at Duv= - 0.0012
- Good news: negative Duv carries benefits of increased color gamut (incl. perceived brightness)

Conclusions

- The chromaticity (Duv) experiment indicates a possibility of new products with preferred color quality.
- Further experiments and/or field experiments (in real applications) are desired to verify the effects of negative Duv.
- NIST keeps working on SSL standards development and research on color quality.

We thank DOE for their support of NIST research.

THANK YOU FOR YOUR ATTENTION.

Contact: ohno@nist.gov